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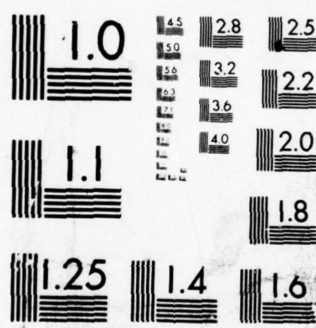

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RESEARCH AND DEVELOPMENT TECHNICAL REPORT

DELET-TR-79-4

MAGNETIC BUBBLE TRAVELING-WAVE AMPLIFIER

Louis J. Jasper, Jr.

ELECTRONICS TECHNOLOGY & DEVICES LABORATORY

February 1979

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A theoretical investigation is presented that exploits the magnetic bubble phenomena for producing a new type of traveling-wave amplifier (TWA) called the Magnetic Bubble Traveling-Wave Amplifier (MBTWA). The theoretical analysis follows the method used by J. R. Pierce in determining the four (4) space charge waves on an elementary electron stream. Calculations include the determination of the propagation constants, velocity-voltage relationship, and gain parameter. Numerical estimates for velocity, voltage, and gain parameter

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#20 ABSTRACT (Contd)

are given. Also, some important aspects of the MBTWA are pointed out which give support to the view that this device could be applicable for high frequency operation in the millimeter wave spectrum.

CONTENTS

MAGNETIC BUBBLE TRAVELING-WAVE AMPLIFIER

INTRODUCTION

Magnetic bubbles (domains) in thin platelets of orthoferrites are currently being utilized to perform logic, memory, and transmission functions. The general formula for an orthoferrite is $MFeO_3$, where M is any rare earth ion. The theories that explain the formation and motion of magnetic bubbles are quite complex. Numerous references are available on this subject. Orthoferrites are normally optically transparent, and magnetic bubbles can be seen by using the Faraday rotation of transmitted light. The general shape and dimensions of the bubbles are determined by the magnetostatic and wall energy balance. Magnetic strip and cylindrical domains can be generated under different operating conditions. This paper considers the formation and transmission of cylindrical domains.

The transmission of the magnetic bubbles from one end of the orthoferrite platelet to the other end is in essence moving entities carrying energy. The conception of the magnetic bubble traveling-wave amplifier (MBTWA) came about from the opinion that these moving entities under the proper conditions can be made to give up their energy. The magnetic bubbles are magnetic dipoles that produce magnetic surface charges. The transmission of the magnetic dipoles, therefore, constitutes magnetic surface charges propagating across the orthoferrite platelet. A radio frequency (RF) wave propagating in the vicinity and at about the same velocity as the magnetic surface charges could take energy from these charges under proper conditions. Amplification of the RF wave would result.

With these concepts in mind, the author has conducted an investigation into this matter and has tried to present a simple theory of operation for the MBTWA. It has been determined that the magnetic bubbles support waves analogous to the space charge waves on the electron beam. The characteristics of these waves, presently, are not fully understood. The theory that is presented in this paper is not meant to be complete, however, it is meant to be a starting point for further investigation. The MBTWA is a novel device and it can be of interest only when it can compete with existing microwave devices. The feasibility of the MBTWA is not demonstrated in this paper. It is hoped that this report arouses the curiosity of the reader in an attempt to generate further investigation or research for opportunity.

DESCRIPTION OF THE MAGNETIC BUBBLE TRAVELING-WAVE AMPLIFIER (MBTWA)

Figure 1 shows the arrangement of the MBTWA. There are three (3) essential parts of the MBTWA; one is the meanderline circuit which serves as the means for producing a slow electromagnetic wave, the other is the orthoferrite platelet which is the medium whereby the bubbles are generated and transmitted, and the third is the transmission circuit which is used as the means of forming and transmitting the magnetic bubbles. The meanderline circuit propagates a transverse electric magnetic (TEM) mode in the longitudinal direction, Z. RF matching into and out of the RF circuit are not considered in this paper. The orthoferrite ($MFeO_3$) platelet is a

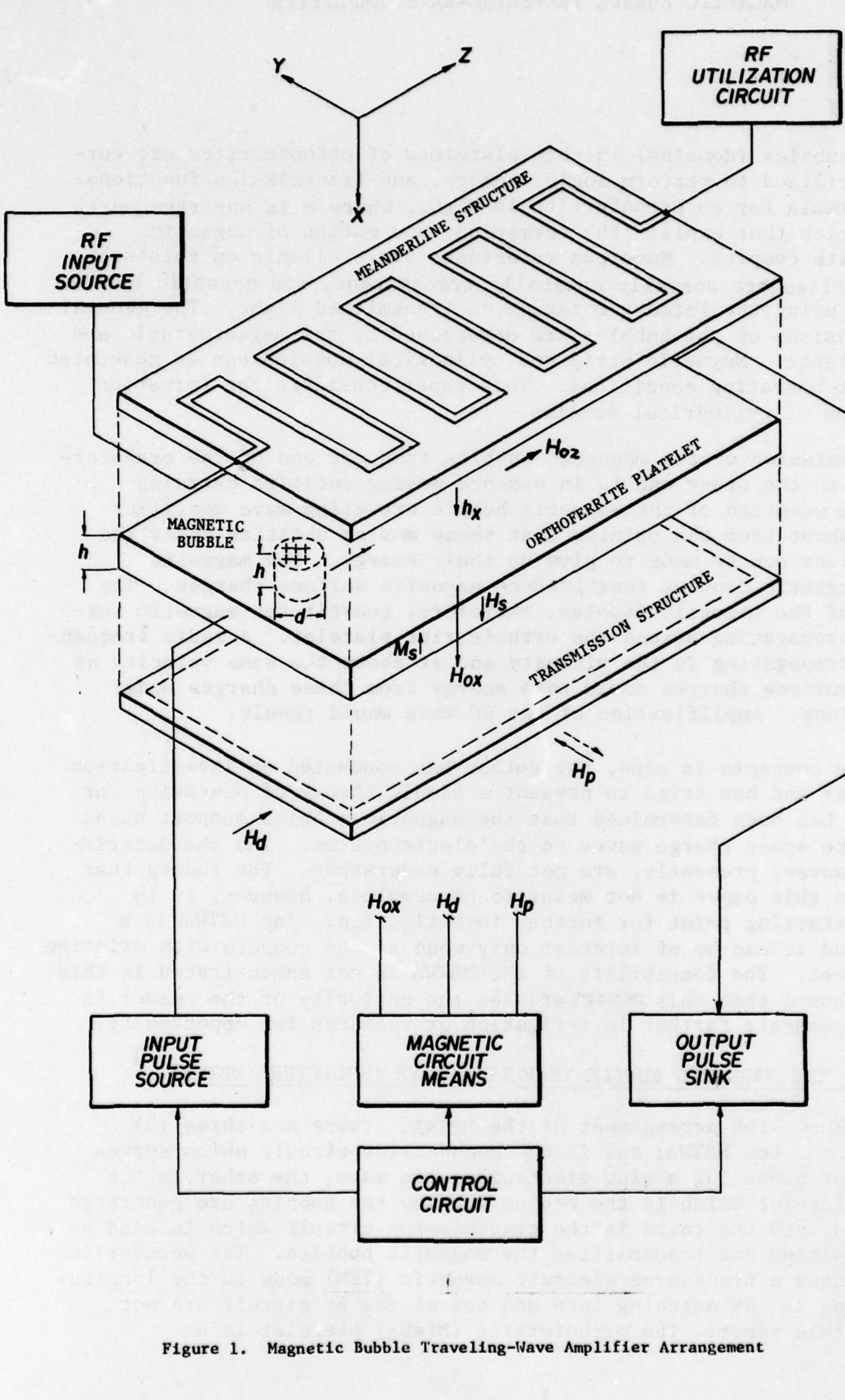

Figure 1. Magnetic Bubble Traveling-Wave Amplifier Arrangement

"just right" platelet. That is, the thickness, h, of the platelet is chosen so that the magnetostatic energy and wall energy are somewhat in balance. This condition forms stable cylindrical domains and the diameter of the domain, d, is approximately equal to the thickness of the platelet ($d \approx h$). The transmission circuit shown in Figure 1 determines the direction as-well-as effects the velocity of the bubbles. The exact details of the transmission circuit are not given in this paper. It is necessary for this application to move the bubbles at a velocity consistent with the velocity of the electromagnetic wave. Typical velocities for the electromagnetic wave range from about 1/10 to 1/100 the velocity of light. A magnetic bubble can be moved about in much the same way as a charged particle. A bubble can be moved one domain diameter in less than 1 nanosecond (ns). This corresponds to a velocity in the order of 10^5 meter/second. Presently no upper limit to the cylindrical domain velocity has been found experimentally. Therefore, a successful device application depends upon the techniques used to generate, propagate, and interact with the bubbles.

There are various techniques used to propagate the magnetic bubbles.[1] Three techniques are briefly described herein. The first technique uses a sequence of current pulses applied to the conductor array (conductor circuit technique). The second requires an in-plane rotating field acting on a structured permalloy pattern (T-Bar Permalloy Circuit Technique). The permalloy pattern generates traveling positive and negative poles. These poles selectively attract and repel a cylindrical domain and thereby control its motion. The third technique (angelfish circuit technique) interacts a pulsating domain with a wedge like permalloy pattern resulting in a unidirectional movement. This author utilizes the T-Bar permalloy circuit technique for manipulation of the cylindrical domains. This method was chosen mainly for convenience of calculations.

Stable domains are maintained in the cylindrical form by an overall uniform bias field applied normally to the platelet surface. The direct current (dc) magnetic field (H_{ox}) shown in Figure 1 is the bias field used to maintain stable magnetic bubbles. This field is given a constant gradient in the Z direction. The H_{oz} field shown in Figure 1 is used as a fictitious field in a magnetostatic equation. The RF magnetic field, h_x, is the actual field and replaces the H_{oz} field in later dynamic calculations. The justification for this manipulation will be explained later.

In Figure 1 thin insulating materials are used to isolate the RF circuit, orthoferrite platelet, and transmission circuits.

THEORETICAL ANALYSIS

This is a simple theory that describes the general circuit and electronic features of the MBTWA. As such, simplifying approximations and assumptions are made and it is hoped that reasonably good results are obtained that describe the roots of the propagation equation. The solution

1. A. H. Bobeck, "Application of Orthoferrites to Domain Wall Devices," IEEE Transactions on Magnetics, Vol. Mag-5, No. 3, pp 544-553, September 1969.

to the problem follows the method of J. R. Pierce[2] for determining the waves on an elementary electron stream. For small signals, a wave-type solution exists. All alternating current (ac) electronic and circuit quantities vary with time and distance as exponent (exp) $[j\omega t - \Gamma Z]$. Γ, is the propagation constant and ω, is the angular frequency. The meanderline circuit propagates a TEM mode and the ratio of the RF electric field (e_z) to the RF magnetic field (h_x) is given by:

$$\frac{e_z}{h_x} = -\sqrt{\frac{\mu}{\varepsilon}} \tag{1}$$

where $\sqrt{\frac{\mu}{\varepsilon}}$ is the impedance. The properties of the meanderline are simulated by a simple delay line or network. Ordinary network equations are applied.

It is assumed that the moving confined magnetic charges on the orthoferrite platelet produce the same effect on the RF circuit as an electron stream would produce on an RF circuit. Since the charges do not exist alone, that is, they are formed from magnetic dipoles, it is further assumed that the separation between poles is sufficient to avoid complications due to interaction with both poles. The magnetic charges within a cylindrical bubble are assumed to have a uniform distribution and travel very close to the RF circuit so that all displacement current due to the presence of the charges flows directly into the line as an impressed current.

The magnetostatic equation gives the total force acting on the cylindrical magnetic bubbles. The magnetic bubbles are assumed to be cylindrical with uniform surface magnetic charges rather than a strip of uniform magnetic surface charges mainly for convenience of calculations. In an actual device, a strip of moving charges could be the preferred embodiment since a larger surface current density could be generated.

The effect the RF circuit produces on the moving magnetic charges is different than the effect produced on an electron stream since the dipole motion is described differently and has a different voltage-velocity relationship. It is considered that there is an interaction between an electric circuit capable of propagating a slow electromagnetic wave and a stream of magnetic surface charges. The signal current in the circuit is the result of the magnetic surface charges acting on the circuit. The disturbance on the magnetic surface charges is the result of the RF fields of the circuit acting on the magnetic surface charges. Thus, the problem consists of two parts.

The first part of the problem concerns the disturbance produced on the RF circuit by the stream of magnetic surface charges. As was previously

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2. J. R. Pierce, "Traveling-Wave Tubes," D Van Nostrand Co. Inc., pp 9-15, 1950.

mentioned, this is assumed to produce the same effect on the RF circuit as does an electron stream. The solution to this part of the problem is, therefore, the same as the solution given by J. R. Pierce. The voltage, V, in the RF line is:

$$V = \frac{-\Gamma \Gamma_1 K i}{\left[\Gamma^2 - \Gamma_1^2\right]} \tag{2}$$

where Γ = propagation constant

Γ_1 = natural propagation constant of the line

K = interaction impedance

i = convection current produced by the stream of magnetic surface charges.

Since it is assumed that all quantities vary with distance as $\exp\left[-\Gamma Z\right]$, differentiation with respect to, Z, can be replaced by multiplication by $-\Gamma$.

The second part of the problem is to find the disturbance produced on the stream of magnetic surface charges by the RF fields of the line. The magnetostatic energy equation which gives the total energy of the magnetic bubble is[3]

$$\xi_T \text{ (total)} = \xi_W \text{ (wall)} + \xi_D \text{ (magnetostatic)} + \xi_{H_a} \text{ (applied)}$$

or
$$\xi_T = 2\pi r h \sigma_W - \xi_D + 2M_s H_a \pi r^2 h \tag{3}$$

using CGS units where

σ_W = domain wall energy

M_s = saturation magnetization

r = radius of the bubble

h = thickness of the orthoferrite platelet

and H_a = applied dc field

$$H_a = H_{ox} + H_{oz} \tag{4}$$

where H_{ox} = dc biasing field

H_{oz} = fictitious dc field (mentioned earlier).

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3. A. H. Bobeck, "Properties and Device Applications of Magnetic Domains in Orthoferrites," Bell System Technical Journal, Vol. XLVI, No. 8, pp 1901-1925, October 1967.

E. Schlömann in his article in Journal Reprint of Raytheon Company[4] demonstrated that a d-c magnetic field (H_{oz}) in the Z direction is equivalent to an RF field (h_x) in the X direction with the relationship

$$H_{oz} = -h_x{}^2 \frac{\gamma}{\omega} \tag{5}$$

where $\gamma = 1.76 \times 10^{11} \frac{\text{rad meter}}{\text{amp sec}}$ (gyromagnetic ratio) and $\omega = 2\pi$ times the frequency. Equation (5) will be used in later dynamic calculations.

The total force on the wall is found by differentiation with respect to r, $(\frac{\partial}{dr})$. Assuming $\frac{\partial \sigma_w}{\partial r}$ is negligible, then the total force on the wall is

$$\frac{\partial \xi_T}{\partial r} = 2\pi h \sigma_W - \frac{\partial \xi_D}{\partial r} + 4\pi r h M_s H_{ox} + 4\pi r h M_s H_{oz} \tag{6}$$

Equation (6) can be expressed in terms of fields by dividing by $4 \pi M_s rh$,

$$\frac{\frac{\partial \xi_T}{\partial r}}{4\pi M_s rh} = H_W - H_D + H_{ox} + H_{oz} \tag{7}$$

where H_W = wall field and H_D = demagnetization field

$$\frac{\sigma_W}{2rM_s} = H_W \quad \text{and} \quad \frac{\partial \xi_D / \partial r}{4\pi M_s rh} = H_D$$

The stability condition for a "just right" platelet is

$$H_W = H_D - H_{ox} \tag{8}$$

therefore Equation (7) becomes

$$\frac{\frac{\partial \xi_T}{\partial r}}{4\pi M_s rh} = + H_{oz} \quad \text{or} \quad \frac{\partial \xi_T}{\partial r} = + 4\pi M_s rh H_{oz} \tag{9}$$

The force per unit area (pressure) on the magnetic bubble is

$$P = 2M_s H_{oz} \tag{10}$$

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4. E. Schlömann, "Domain-Wall Motion Induced by Strong Microwave Fields," Journal Reprints of Raytheon Co., Vol. 12, No. 3, 4, pp 35-38, September, December, 1975.

Equation (10) is identical to the pressure equation on a domain wall as given by E. Schlömann

$$\text{Let } \frac{\partial \xi_T}{\partial r} = M_b \frac{dV}{dt} \tag{11}$$

where M_b = mass of the magnetic bubble

and V = velocity of the bubble

$$\frac{dV}{dt} = \frac{\partial V}{\partial t} + \frac{\partial V}{\partial Z}\frac{dZ}{dt} \tag{12}$$

where $V = \frac{dZ}{dt} = U_o + W$ and

U_o = average dc velocity, W = a-c velocity and $W \ll U_c$

Equation (12) can be rewritten

$$\frac{dV}{dt} = (j\omega - U_o \Gamma)V \tag{13}$$

and the total force on the magnetic bubble (Equation (11)) can be expressed as

$$M_b(j\omega - U_o \Gamma)V = 4\pi M_s \, rh \, H_{oz}$$

$$\text{or } V = \frac{4\pi M_s rh \, H_{oz}}{U_o M_b \, (j\beta_e - \Gamma)} \tag{14}$$

where $\beta_e = \frac{\omega}{U_o}$

The fictitious H_{oz} field is now replaced by the RF field (h_x) as given in Equation (5)

$$V = \frac{-4\pi M_s rh \, h_x^2 \frac{\gamma}{\omega}}{U_o M_b \, (j\beta_e - \Gamma)} \tag{15}$$

Equation (15) is a macroscopic equation that defines the velocity. To go from the macroscopic realm to the microscopic realm, one introduces the magnetic moment where $M_s = \mu_d N$, μ_d = magnetic moment per unit volume and N = total number of dipoles in the volume (bubble).

Assume a uniform distribution of magnetic charges on the surface areas of the cylindrical bubble and that the interaction takes place only with charges on the top area of the cylindrical bubble also, let M_b = 2N times

the mass of a unit charge. Therefore $M_b = 2NM_q$

where M_q = mass of a unit charge

Equation (15) now becomes

$$V = \frac{-\pi \mu_d h^2 h_x^2 \frac{\gamma}{\omega}}{U_o M_q (j\beta_e - \Gamma)} \tag{16}$$

where h = 2r "just right" platelet.

$$\text{Let } M_d = \mu_d \pi \frac{h^3}{4} \tag{17}$$

where M_d = magnetic dipole moment

therefore Equation (16) is:

$$V = \frac{-8 \frac{M_d}{h} h_x^2 \frac{\gamma}{\omega}}{2 U_o M_q (j\beta_e - \Gamma)} \tag{18}$$

The magnetic dipole moment can be expressed in terms of the angular momentum which holds for orbital motion even on the atomic scale.

$$\text{That is } M_d = \gamma L \text{ or } M_d = \gamma M_q \frac{h^2}{4} \omega_o \tag{19}$$

where γ = gyromagnetic ratio

L = angular momentum

$\frac{h}{2}$ = radius of spin where h = 2r

and ω_o = 2π times the precession frequency

A condition is imposed on the RF magnetic field. This allows the root equation for the propagation constant to be of the 4th degree in Γ, so that any disturbance of the circuit and the magnetic charge stream can be expressed as the sum of four waves. Using this condition and the relationship given by Equation (1) gives

$$h_x = \frac{\omega}{\gamma} \quad \text{and} \quad h_x = \frac{-\Gamma V}{\sqrt{\mu/\epsilon}} \tag{20}$$

(condition)

Equation (20) gives the RF magnetic field strength as a function of frequency and also as related to the RF electric field strength.

Substituting equations (19) and (20) into Equation (18) gives:

$$V = \frac{2\gamma\omega_o \Gamma V}{2\sqrt{\frac{\mu}{\epsilon}}\, U_o (j\beta_e - \Gamma)} \qquad (21)$$

The continuity equation or conservation of charge equation is now used and is derived by J. R. Pierce.

$$i = \frac{j\beta_e \rho_o V}{(j\beta_e - \Gamma)} \qquad (22)$$

where $\rho_o = \frac{I_o}{U_o}$

ρ_o = average charge per unit length

and I_o = average convection current.

Using Equation (21), the a-c component of the convection current is:

$$i = \frac{2j\beta_e\gamma\omega_o h\Gamma I_o V}{2\sqrt{\frac{\mu}{\epsilon}}\, U_o^2 (j\beta_e - \Gamma')^2} \qquad (23)$$

The derivation of the average dc velocity, $|U_o|$, is [5]

$$|U_o| = \left(\frac{1}{2}\mu_w|\Delta H_{ox}| - \frac{8}{\pi}H_c\right) \qquad \text{or}$$

$$|U_o| = \left(\frac{1}{2}\mu_w|\Delta H_{ox}|\right) \qquad (24)$$

for $\Delta H_{ox} > \frac{8}{\pi} H_c$, μ_w = wall mobility

and H_c = coercivity of the orthoferrite platelet.

$$\Delta H_{ox} = \frac{\partial H_{ox}\, d}{\partial z}$$

and d = h (diameter of the magnetic bubble), therefore, Equation (24) becomes

$$U_o = \frac{\mu_w}{2}\, h\, \frac{\partial H_{ox}}{\partial z} \qquad (25)$$

where $\frac{\mu_w}{2} = \mu_b$ and μ_b = bubble (domain) mobility.

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5. A. J. Perneski, "Propagation of Cylindrical Magnetic Domains in Orthoferrites," IEEE Transactions on Magnetics, Vol. Mag-5, No. 3, pp 554-557, September 1969.

U. F. Gianola[6] has derived the wall mobility under the assumption of Gilbert dumping.

The wall mobility is:

$$\mu_w = \frac{\gamma \ell_{wg}}{\alpha \pi} \tag{26}$$

where α = Gilbert dumping constant

and ℓ_{wg} = generalized wall width

but $\ell_{wg} = \frac{4\pi A}{\sigma_w}$ or $\ell_{wg} = \pi\sqrt{\frac{A}{K_\mu}}$ (27)

where A = isotropic exchange constant

and K_μ = uniaxial anisotropy constant

The ratio of preferred domain diameter to the domain wall width is by A. A. Thiele[7]

$$\frac{h}{\ell_{wg}} = \left(\frac{16}{\pi}\right)q \quad \text{or} \quad \ell_{wg} = \frac{h\pi}{16\,q} \tag{28}$$

where $q = \frac{K_\mu}{2\pi M_s^2}$

Equation (26) becomes

$$\mu_w = \frac{\gamma h}{16\,q\,\alpha} \tag{29}$$

and Equation (25) becomes

$$U_o = \left(\frac{\gamma h^2}{32\,q\,\alpha}\right)\frac{\partial H_{ox}}{\partial z} \tag{30}$$

One can consider the isotropic exchange constant A, to be fixed and then choose preferred values for the domain diameter and ratio, q. This author chooses the domain diameter = h. If q were less than one, then the domain wall width would be larger than the domain diameter, and in essence no domains would exist. Therefore, q is greater than one.

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6. U. F. Gianola, "Material Requirements for Circular Magnetic Domain Devices," IEEE Transactions on Magnetics, Vol. Mag-5, No. 3, pp 558-561, September 1969.

7. A. A. Thiele, "Device Implications of the Theory of Cylindrical Magnetic Domains," The Bell System Technical Journal, Vol. 50, No. 3, pp 725-773, March 1971.

Also, for very large values of q, the velocity of the domains would be small, since q is inversely proportional to U_o. Since large velocities are desirable for this type application, the author chooses a preferred value of q equal to 3.

When the dc magnetic field (H_{ox}) has a uniform gradient in the Z direction, it can be expressed as a linear equation with distance

$$H_{ox} = QZ + b \quad \text{and} \quad \frac{\partial H_{ox}}{\partial Z} = Q \tag{31}$$

where Q and b are constants.

Setting $\dfrac{\partial H_{ox}}{\partial Z} = Q$ and $q = 3$, then Equation (30) becomes

$$U_o = \frac{\gamma h^2 Q}{96\, a} \tag{32}$$

The convection current, i, can now be expressed in terms of Equation (32).

$$i = \frac{j\beta_e I_o \Gamma V}{2\,(j\beta_e - \Gamma)^2} \left[\frac{1.8\text{X}10^4\ \omega_o\, a^2}{\sqrt{\frac{\mu}{\epsilon}}\ \gamma h^3 Q^2} \right] \tag{33}$$

The above term in brackets has units of volt $^{-1}$, therefore Equation (33) can be written in terms of an effective voltage.

$$\text{Let} \quad V_o = \frac{\sqrt{\frac{\mu}{\epsilon}}\ h^3 \gamma Q^2}{1.8\text{X}10^4\, \omega_o\, a^2} \quad \text{or} \quad V_o = \frac{U_o^2 \sqrt{\frac{\mu}{\epsilon}}}{2h\ \omega_o} \tag{34}$$

where V_o is an effective voltage. Therefore,

$$i = \frac{j\ \beta_e\ I_o\, \Gamma V}{2\, V_o\ (j\,\beta_e - \Gamma)^2} \tag{35}$$

Equation (35) is identical to Equation (2.22) done by J. R. Pierce.[8] However, the voltage-velocity relationship for Pierce's equation is $U_o = \sqrt{2\eta V_o}$ and the voltage-velocity relationship as given in Equation (34) is:

$$U_o = \left[\sqrt{\frac{h\,\omega_o}{(\mu/\epsilon)^{\frac{1}{2}}}} \right] \sqrt{2\gamma V_o} \tag{36}$$

Note that γ and η have the same numerical value but different units. One can now follow Pierce's method of solution. Equation (2) gives the convection current in terms of voltage and Equation (35) gives

8. J. R. Pierce, "Traveling-Wave Tubes," D Van Nostrand Co. Incl, pp 9-15, 1950.

the voltage in terms of convection current. Any value of, Γ, that satisfies both of these equations gives the mode of propagation. Assume, that the speed of the magnetic charges is equal to the speed of the wave in the absence of charges and assume that the propagation constant, Γ, differs from β_e by a small amount, ξ, so that

$$-\Gamma_1, = -j\,\beta_e \quad \text{and} \quad -\Gamma = -j\,\beta_e + \xi$$

Since $\beta_e >> \xi$, terms of $\beta_e \xi$ and ξ^2 can be dropped when appropriate.

Combining Equation (2) and Equation (35) gives

$$1 = \frac{j\,K\,I_o\,\beta_e \Gamma^2 \Gamma_1}{2 V_o\,(\Gamma_1^{\,2} \quad \Gamma^2)\,(j\beta_e - \Gamma)^2} \tag{37}$$

which reduces to

$$\xi^3 = j\beta_e^3 \left(\frac{KI_o}{4V_o} \right) \tag{38}$$

Let $C^3 = \dfrac{KI_o}{4V_o}$ and $\delta = (-j)^{1/3}$

where C = gain parameter

Then $\boxed{\xi = \beta_e C \delta}$ (39)

Equation (39) is the root equation for the propagation constants. The 4th root was eliminated by the approximations made above. The three waves are forward waves and the 4th wave is a backward wave with a propagation constant

$$-\Gamma = j\,\beta_e \left(1 - \frac{C^2}{4}\right) \tag{40}$$

In the following section, numerical estimates are given for the effective voltage, V_o, average d-c velocity, U_o, and the gain parameter, C. The numerical estimate for C, indicates that C is indeed small and the approximations made above are reasonable.

NUMERICAL ESTIMATES OF THE PARAMETERS OF THE MBTWA

In an attempt to obtain a better understanding of the theory of operation for the MBTWA, numerical estimates are given for the voltage, velocity, gain parameter, and other terms needed to calculate the above three parameters.

A maximum and minimum condition can be found for $Q\ (\frac{\partial H_{oz}}{\partial Z})$, the bias field gradient. Equation (32) has an upper limit since the average d-c velocity must be less than the velocity of light, c.

Therefore,

$$Q < \frac{96\alpha c}{\gamma h^2} \tag{41}$$

Also to overcome wall coercivity H_c, the condition below must be met:

$$\Delta H_{ox} > \frac{8\ H_c}{\pi} \quad \text{or} \quad Qh > \frac{8\ H_c}{\pi} \tag{42}$$

The upper and lower limits for Q are:

$$\frac{8\ H_c}{\pi\ h} < Q < \frac{96\alpha c}{\gamma h^2} \tag{43}$$

Equation (43) indicates that H_c and h have maximum values consistent with a given damping constant, α, and necessary to propagate and maintain stable domains.

As an example of the application of Equation (43), if one chooses $H_c = 0.1$ oersteds (8 amp m^{-1}), $\alpha = 10^{-2}$, and $h = 1 \times 10^{-6}$ m, then Equation (43) gives

$$20.4 \times 10^6 < Q < 16.4 \times 10^8\ \frac{\text{amp}}{m^2} \left(\begin{matrix}\text{mks}\\ \text{units}\end{matrix}\right) \tag{44}$$

Also, an estimate can be found for the mean velocity, U_o, by using Equation (32) and a value for Q chosen from Equation (44) to be 10^7 amp m^{-2}.

Then $$U_o \approx 1.8 \times 10^6\ \frac{m}{sec} \tag{45}$$

The ratio $\frac{U_o}{c}$ for a range of voltages, V_o, is given in Table 1.

Equation (36) is used to calculate the $\frac{U_o}{c}$ ratio. Assumed values for h, ω_o, and $\sqrt{\frac{\mu}{\epsilon}}$ are:

$$h = 10^{-6}\ m,\ \omega_o = 25\ \text{MHz},\ \text{and}\ \sqrt{\frac{\mu}{\epsilon}} = 100\ \Omega$$

Table 1

The Ratio $\frac{U_o}{c}$ For Several Voltages, $\mathcal{V}_o$

$\mathcal{V}_o$ (volts)	$\frac{U_o}{c}$
1	0.001
10	0.003
100	0.010
1000	0.031

$$\sqrt{\frac{h\,\omega_o}{(\mu/\epsilon)^{\frac{1}{2}}}} = \frac{1}{2}\,\Omega^{-\frac{1}{2}}$$

In obtaining a reasonable estimate for the gain parameter C, the interaction impedance, K, must be known. Theoretical calculations of K, for a meanderline circuit in conjunction with an electron beam have been solved. The calculations involve the solutions to Maxwell's equations subject to the appropriate boundary conditions. The configuration and current density of an electron beam in vicinity to the meanderline RF circuit must be considered. The electrons closest to the RF circuit play a more important role in the interaction process since the magnitudes of the RF fields decrease rapidly away from the RF circuit. As an example for the helix circuit, one tries to obtain a filling factor (radius of electron beam to the radius of the helix) as close to a value of 1 which is consistent with heat dissipation and focussing considerations. For the MBTWA, the flow of magnetic charges are restricted to the surface of the orthoferrite and as such are very close to the meanderline RF circuit except for a thin sheet of dielectric material which is required to electrically isolate the RF circuit and meanderline. The relative dielectric constants of both the dielectric sheet and orthoferrite will have the effect of reducing the magnitudes of the RF fields and consequently, K. Therefore, low dielectric constants are desirable for this aspect. The author in this report has not attempted to calculate the interaction impedance K as related to the MBTWA. However, knowing the RF characteristics of the meanderline, an intuitive estimate for K which would be expected is to give K the value of about 1 ohm at frequencies in the order of 1 gigahertz (GHz). This value for K, is an assigned value and its only importance is that it allows for a crude estimate for the gain parameter C. Taking this liberty, the value of C, is estimated to be about 0.02 for $I_o \approx 10^{-3}$ amp, $\frac{U_o}{c} \approx 0.006$, and $\mathcal{V}_o \approx 37$ volts.

One interesting aspect of the MBTWA is to look at the condition

(Equation (20)) imposed on the RF magnetic field, h_x, in order to obtain the wave solutions. The condition that $\omega = \gamma h_x$ indicates the possibility of operation at very high frequencies (millimeter range). For example,

Equation (20) can be expressed in terms of the free space wave length. λo as:

$$\lambda_o = \frac{2\pi c}{\gamma h_x} \tag{46}$$

For h_x = 0.1 oersteds (8 amp m^{-1}) then λ_o = 1.3 mm.

CONCLUSIONS

In this report, the magnetic bubble phenomena has been exploited to describe a novel microwave amplifier, the MBTWA. Assumptions and approximations regarding RF circuit and orthoferrite parameters were made and the equations resulting from the theoretical analysis are slow-wave solutions. The analysis indicates that the slow-waves of the magnetic bubbles are analagous to the space charge waves of an elementary electron beam. Also, the analysis indicates that the device could be made to operate at very high frequencies in the millimeter wave spectrum. Numerical estimates have been found for important operating parameters of the MBTWA. These operating parameters have not been optimized nor a working model of the MBTWA demonstrated. The author has by no means investigated all practicable physical arrangements of the MBTWA and all possible techniques for propagating magnetic bubbles. This report is intended to give the reader some insight into the nature of the MBTWA and to give a theoretical treatment of the device in which one can use as a starting point for further investigations.